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Life Cycle Assessment of Low-Carbon Fuels

Lafarge Exshaw Cement Plant Kiln 6 – Greenhouse Gas Emissions Life Cycle Assessment

Version A

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This document is an independent report prepared exclusively as information for Lafarge Canada (Lafarge). This report is based on an analysis conducted in a spreadsheet entitled "Lifecycle GHG emissions from the Lafarge Exshaw plant (Kiln 6)" and delivered to Lafarge.

The views and opinions expressed in this report are those of the authors.

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Executive summary

This assessment is part of a larger project led by Lafarge Canada Inc. (Lafarge), to study the environmental risks and benefits of switching from fossil fuels to waste products as kiln fuel at its Exshaw cement plant in Alberta.[1] The full research project, involving Lafarge, the University of Calgary, Queen's University and the Pembina Institute, includes lab simulations and environmental studies, as well as feedstock logistics and characterization in the regional context.

The Pembina Institute and the University of Calgary undertook the life cycle assessment (LCA) of the greenhouse gas emissions (GHG) associated with switching from fossil fuels to waste products as fuel for a cement kiln. The Pembina Institute developed the LCA using internationally recognized practices; in an upcoming phase, researchers from the University of Calgary will conduct a critical review of the LCA and explore related research questions. This report explains the methodology employed for the LCA, outlines the main findings, discusses some of the assumptions through a sensitivity analysis, and proposes further research questions for the University of Calgary to explore.

In summary, Lafarge is considering using alternative fuels to replace natural gas at Kiln 6 of the Exshaw cement plant. One particular topic of interest is the potential reduction in GHG emissions from the use of alternative fuels. To this end, a life cycle assessment of GHG emissions from the production of clinker at Kiln 6 of the Lafarge cement plant was performed. Nine alternative fuels and a mix of these fuels, as provided by Lafarge, were considered for use in displacing natural gas.

Three fuel scenarios were assessed:

1. Business-as-usual scenario, where the kiln is fired with natural gas;
2. Substitution of all of the natural gas with alternative fuels, which quantifies the maximum fuel switch GHG emissions reductions;[2]
3. Half of the natural gas is replaced with the alternative fuel.

[1] The overarching research project is funded by Lafarge, Alberta Innovates, Ontario Centres of Excellence, Emissions Reduction Alberta, and the Natural Sciences and Engineering Research Council of Canada.

[2] Emissions reductions achieved in this scenario are theoretical and cannot be achieved in practice since a minimum volume of fossil fuels is required to fire the kiln.

An additional pathway was considered by assessing the emissions avoided in diverting waste from the landfill for use as kiln fuel. Finally, a sensitivity analysis was conducted to determine the impact of the methane leak rate and global warming potentials (GWP) on the results using the fuel mix proposed by Lafarge.

The results of the LCA are as follows:

- Fuels with a high biogenic carbon content — that is, those mainly derived from biomass as opposed to fossil fuels — reduce GHG emissions the most, on the order of 9-12%, with a 50% substitution rate. These fuels include construction and demolition waste, railway ties, wood and natural textiles.
- The reduction in GHGs is primarily due to the assumption that biogenic fuels are carbon neutral, meaning their combustion emissions are not counted.
- Fuels with a high biogenic carbon content also have the highest avoided landfill emissions, in the range of 21–26% of total GHG emissions, assuming a 50% substitution rate.
- The methane leak rate and GWP used have an impact on the expected GHG reductions from the use of alternative fuels in the kiln. The GHG emissions reductions for the Lafarge fuel mix increase from 8.2 to 13.0% when a 2.3% methane leak rate and methane GWP of 86 are used. The 2.3% methane leak rate is the most recent estimate based on studies conducted in the United States.[3]

In the next phase of this project, researchers from the University of Calgary will be investigating the life cycle GHG emissions in more detail. The Pembina Institute recommends exploring some or all of the following:

- Update the alternative fuel properties with those from the study characterizing alternative fuels available in the Calgary region.[4]
- Determine landfill methane generation from waste materials more accurately using a first order model.
- Evaluate the amount of methane capture currently occurring at Alberta landfills — Calgary in particular — and the addition of landfill scenarios that assume some methane is captured.
- Reconcile the time frames of different parts of the model, including the methane emissions GWP and the landfill emissions.

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[3] Ramon Alvarez et al, "Assessment of methane emissions from the U.S. oil and gas supply chain," *Science* (2018), DOI: 10.1126/science.aar7204

[4] Alternative fuels' properties used in this analysis were sourced from similar projects and are not specific to the Calgary context. As part of its mandate in this project, the University of Calgary has hired a consulting company to conduct a characterization of alternative fuels available in the Calgary region.

- Further analyze the carbon neutrality of biomass fuels, potentially using the method employed in the study from the Laurentian Forestry Centre.[5]
- Examine uncertainties of waste fuel combustion emission factors.

[5] Jérôme Laganière et al, "Range and uncertainties in estimating delays in greenhouse gas mitigation potential of forest bioenergy sourced from Canadian forests," 9, no. 2, (2015), https://onlinelibrary.wiley.com/doi/full/10.1111/gcbb.12327

1. Introduction

1.1 Introduction

Lafarge is considering the use of alternative fuels to substitute some of the natural gas currently used in Kiln 6 at its Exshaw cement plant. One of the topics of interest is the potential reduction in greenhouse gas emissions (GHGs) that could be achieved by using alternative fuels. The Exshaw cement plant currently uses natural gas as the kiln fuel.[6] Nine alternative fuels (also referred to as low-carbon fuels, or LCFs) have been identified by Lafarge as potential substitutes for natural gas:

- Construction and demolition waste
- Asphalt shingles
- Plastics
- Railway ties
- Wood
- Rubber
- Tire fluff
- Carpet
- Natural textiles

The majority of GHG emissions from cement production come from the calcination of limestone and kiln fuel combustion. A complete life cycle assessment (LCA) is conducted to assess the potential reduction in GHG emissions along the supply chain.

This analysis is part of a larger research project aiming at better understanding the environmental risks and benefits of switching from fossil fuels to waste products as fuel for a cement kiln.[7] In this context, the Pembina Institute and the University of Calgary undertook the LCA of the GHG associated with switching from natural gas to waste products for firing the cement plant's main kiln. The Pembina Institute developed the LCA using internationally recognized practices; in an upcoming phase, researchers from

[6] Although the plant is also permitted to burn coal, Lafarge indicated that the cement kiln has been solely running on natural gas for the past couple of years.

[7] The overarching project includes lab simulations, environmental studies as well as feedstock logistics and characterization in the regional context; and involves teams from Lafarge, the Pembina Institute, the University of Calgary and Queen's University. This research project is funded by Lafarge, Alberta Innovates, Ontario Centres of Excellence, Emissions Reduction Alberta, and the Natural Sciences and Engineering Research Council of Canada.

the University of Calgary will conduct a critical review of the LCA and explore related research questions.

This report presents the preliminary results of the LCA of GHG emissions. Section 1 outlines the scope of work, system boundary, fuel scenarios and pathways considered. Section 2 explains the methodology used in conducting the LCA. Section 3 presents the results for each scenario and pathway, along with a sensitivity analysis. Sections 4 and 5 state the conclusions and recommendations for next steps.

1.2 Scope of work

The goal of the study is to understand the change in life cycle GHG emissions from substituting a portion or all of natural gas with alternative fuels. The assessment is limited to the production of clinker in Kiln 6 at the Exshaw cement plant. A suite of alternative fuels was considered, based on data provided by Lafarge. The local availability of these fuels is not considered here. A separate supply chain assessment on the availability and characterization of local fuels is currently being conducted by a consulting company.

The LCA includes all emissions from cradle to gate as shown in Figure 1. This includes emissions from the extraction, transport, and processing of raw materials and fuels through to the production of clinker on-site. Indirect emissions from electricity use are also included. Emissions from sources enclosed in a dotted line in the diagram were not deemed to be material and are not included in the analysis.

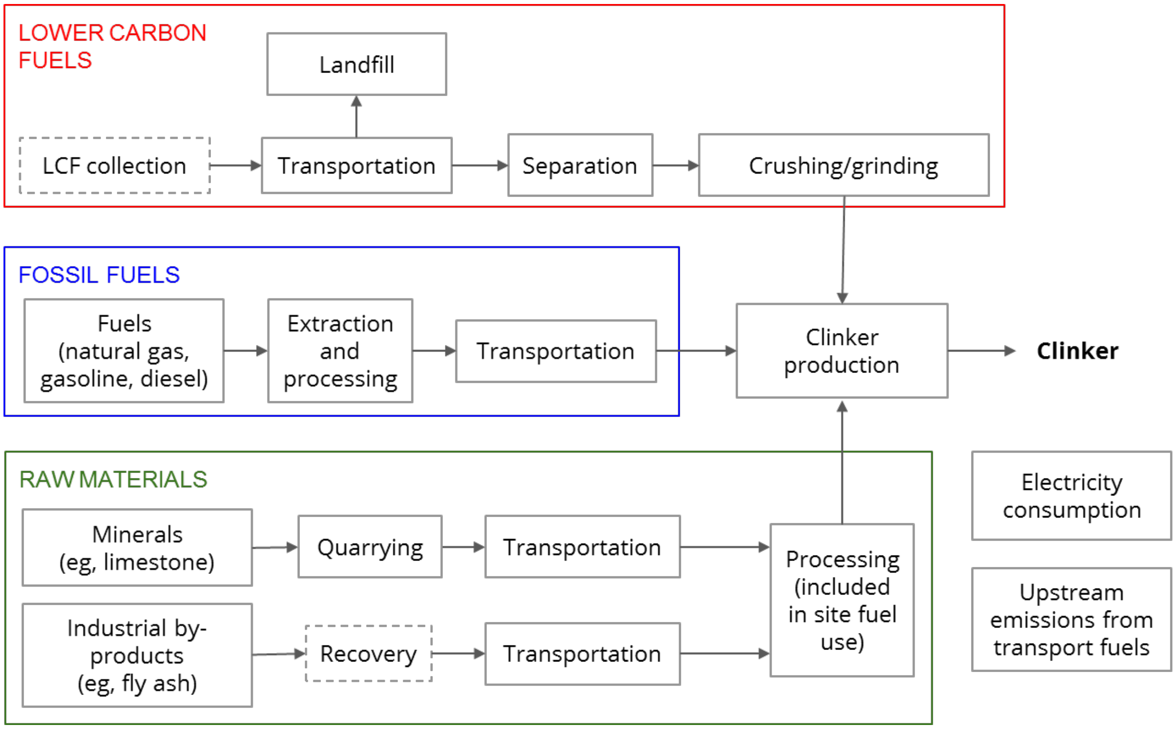

Figure 1. Life cycle assessment system boundary

The assessment does not include any downstream emissions that occur after the production of clinker, such as the production of cement using clinker, the packaging, end use and end-of-life recycling of the cement. Emissions associated with one-time capital investments such as construction and startup of the plant were also not included. Only emissions associated with continuous operation of the plant were considered.

Emissions from the collection and storage of the alternative fuels were not included, because their contribution was judged to be immaterial. Similarly, the recovery of industrial by-products used as a raw material in the kiln was estimated insignificant in terms of energy use and GHG emissions.

The World Business Council for Sustainable Development (WBCSD) provides guidance on the full range of Scope 3 emissions that should be included in a complete LCA.[8] This document was used to determine meaningful sources of indirect emissions that should be included in this analysis.

[8] World Business Council For Sustainable Development, *Cement Sector Scope 3 GHG Accounting and Reporting Guidance* (2016). https://docs.wbcsd.org/2016/11/Cement_Sector_Scope3.pdf

1.3 Scenarios

Three scenarios were considered in the assessment. The first is the baseline scenario where natural gas is burned in the kiln for clinker production. The second two scenarios consider the use of waste fuels substituted for natural gas, at two substitution rates (50% and 100%) as shown in Table 1.[9]

Table 1. Assessment scenarios

Scenario	Description
Baseline	Natural gas is used as the kiln fuel.
100% fuel substitution	All of the natural gas is replaced with waste fuels. Each alternative fuel is assessed individually.
50% fuel substitution	Half of the natural gas is replaced with waste fuels based on substitution rates stated by Lafarge. Each alternative fuel is assessed individually.

Although the 100% fuel substitution scenario is unrealistic from a technical perspective, it serves the purpose of estimating the maximum GHG reductions achievable by a given LCF. The 50% fuel substitution scenario is somewhat more realistic, as this substitution rate is achieved or neared nationally in many European countries. Table 2 shows alternative fuel use reported across twelve countries around the world.

Table 2. Cement kiln fuel substitution rates across different countries and regions

Country/Region	% Substitution
Netherlands (2011)	85
Belgium (2011)	60
Germany (2010)	53.6
Sweden (2011)	45
Poland (2010)	45
Switzerland (2012, only Holcim)	41
Spain (2011)	22.4

[9] The LCA tool developed by Pembina allows easy testing of other substitution rates.

EU (2012)	18
Japan (2012)	15.5
Canada (2008)	11.3
USA (2004)	8
Australia (2013)	7.8

Source: Rahman et al.[10]

In addition to these scenarios, a sensitivity analysis was conducted for the fuel mix described by Lafarge.[11] The effect of the methane leak rate and the global warming potential of methane were included in this analysis.

1.4 Pathways

Two pathways were considered as a part of this assessment. The first is the clinker production pathway, which includes all emissions from cradle-to-gate from the extraction and processing of raw materials and fuels to clinker production. The second pathway considers the fate of the waste materials if they were not used as fuel in the kiln, but sent to the landfill, where their decomposition leads to methane emissions.

The clinker production pathway investigates the potential for reducing GHG emissions by using waste materials as kiln fuel (in combination with, or in place of, natural gas). The landfill pathway adds an additional layer by examining the additional GHG savings from the generation of methane by the materials if they were sent to landfill and the transport of those materials to the landfill.

[10] Azad Rahman et al., "Recent Development on the Uses of Alternative Fuels in Cement Manufacturing Process," *Fuel*, 145 (April 2015), 84, doi:10.1016/j. fuel.2014.12.029

[11] Lafarge, *Assessing the role of low carbon fuels in reducing carbon emissions from cement plants* (2017). http://lafargeexshaw.ca/wp-content/uploads/2017/10/Assessing-the-role-of-low-carbon-fuels.pdf

2. Life cycle emissions methodology

2.1 Introduction

Life cycle GHG emissions are presented per tonne of clinker produced, as is standard for life cycle inventories of cement production. GHG emissions are expressed in tonnes of carbon dioxide equivalent and calculated by multiplying the GHG emission factor (GHG emissions per mass of fuel or material, kWh of electricity, or t-km of transportation) by the consumption rate.

2.2 Raw material extraction

Raw material quantities consumed annually in Kiln 6 were provided by Lafarge. Emission factors for raw material extraction were sourced primarily from Zhang and Mabee.[12] Iron, bottom ash and sand are sourced from third-party suppliers and considered to be waste products that would otherwise require disposal. GHG emissions from the extraction of soil were assumed to be insignificant. Limestone is produced on-site and the extraction emissions are included in the site diesel, gasoline and propane use. However, these emissions are small compared those calculated using the emission factor from Zhang and Mabee. To obtain a conservative estimate of limestone extraction emissions, the higher emission factor was used.

Table 3. Raw material extraction emissions

Raw material	Activity (t/yr)	Emission factor (t CO_2e/t material)	CO_2e emissions (t/yr)
Limestone	1,612,992	0.0355[13]	57,261
Black shale	109,952	0.0026[14]	284

[12] Linghong Zhang and Warren E. Mabee, "Comparative study on the life-cycle greenhouse gas emissions of the utilization of potential low carbon fuels for the cement industry," *Journal of Cleaner Production* 122 (2016).

[13] Ibid

[14] Worley Parsons Komex, "Exshaw Plant Approval Renewal Application/Expansion Project, Volume II: Environmental Screening Report 5. Greenhouse Gas Assessment," Spreadsheet, 2007

Sandstone	59,041	0.0133[15]	785
Red shale	89,927	0.0026[16]	232
Lime	2,409	1.2[17]	2,891

2.3 Raw material transport

Raw material source locations and transport methods were provided by Lafarge. Materials are transported using diesel-powered trucks and diesel-powered trains. Transport distances were estimated using Google Maps. Transport emission factors from GHG Protocol[18] were used for diesel truck and rail transport.

Table 4. Raw material transport emissions

Raw material	Activity (t/yr)	Transport distance (km)	Transport method	Emission factor (t CO_2e/ t material)[19]	CO_2e emissions (t/yr)
Limestone	1,612,992	1	Diesel truck	2.04E-04	329
Black shale	109,952	11	Diesel truck	2.04E-04	247
Sandstone	59,041	11	Diesel truck	2.04E-04	132
Pit run	41,945	11	Diesel truck	2.04E-04	94
Iron - Ipsco EVRAZ	7,683	875	Rail	1.74E-05	117
Iron - Alta Steel	7,683	375	Diesel truck	2.04E-04	588
Iron - Gerdau	7,683	1470	Rail	1.74E-05	197
Soils	19,166	1	Diesel truck	2.04E-04	4

15 Zhang and Mabee, "Comparative Study."

16 Worley Parsons Komex, "Exshaw Plant Approval."

17 United States Environmental Protection Agency, "AP 42, Fifth Edition, Volume 1, Chapter 11.17 Lime Manufacturing (1998)," https://www3.epa.gov/ttn/chief/ap42/ch11/final/c11s17.pdf

18 Greenhouse Gas Protocol, "GHG Emissions from Transport or Mobile Sources," spreadsheet, May 2015, https://ghgprotocol.org/sites/default/files/Transport_Tool_v2_6.xlsx

19 Ibid

Raw material	Activity (t/yr)	Transport distance (km)	Transport method	Emission factor (t CO_2e/ t material)[19]	CO_2e emissions (t/yr)
Bottom ash	99,054	440	Diesel truck	2.04E-04	8,891
Red shale	89,927	650	Rail	1.74E-05	1,018
Lime	2409	8	Diesel truck	2.04E-04	4
Sand	723	176	Diesel truck	2.04E-04	26

2.4 Fuel extraction

Site consumption data for kiln fuel (natural gas) and non-kiln fuels (diesel, gasoline and propane) were provided by Lafarge. Fraction of fuel used at Kiln 6 was estimated by Lafarge based on the fraction of clinker produced at Kiln 6 compared to the total on-site clinker production. Fuel extraction emissions include emissions associated with the energy used to physically extract, process and transport the fuel as well as any fugitive, venting and flaring emissions occurring during these stages.

The natural gas extraction emission factor was determined through an analysis of the 2018 National Inventory Report (NIR) using 2016 data.[20] This analysis is documented in Appendix B and aims to better represent the total upstream emissions from natural gas production, processing and transport with a specific emphasis on the impact of fugitive, vented and flared methane emissions. The leakage rate of methane calculated from the NIR data is 0.70%; however, a multitude of studies in Canada and the United States have shown the methane emissions from oil and gas are significantly underestimated.[21,22,23] A 100-year methane global warming potential (GWP) of 28 was used to convert methane

[20] Environment and Climate Change Canada, *National Inventory Report 1990-2016: Greenhouse Gas Sources and Sinks in Canada*, 2018. https://unfccc.int/sites/default/files/resource/can-2018-nir-13apr18.zip

[21] Emmaline Atherton et al., "Mobile measurement of methane emissions from natural gas developments in Northeastern British Columbia, Canada," *Atmospheric Chemistry and Physics Discussions*, 17 (2017), 12405, http://www.atmos-chem-phys-discuss.net/acp-2017-109/acp-2017-109.pdf

[22] Ramon Alvarez et al, "Assessment of methane emissions from the U.S. oil and gas supply chain," *Science* (2018), DOI: 10.1126/science.aar7204

[23] Matthew Johnson et al, "Comparisons of Airborne Measurements and Inventory Estimates of Methane Emissions in the Alberta Upstream Oil and Gas Sector," *Environmental Science and Technology*, 51, no. 21 (2017), 13008, DOI: 10.1021/acs.est.7b03525

emissions to carbon dioxide equivalent, based on results in the IPCC's fifth assessment report.[24] Methane only stays in the atmosphere for about a decade, and so it has a large immediate impact on the climate. On a 20-year timescale, the GWP of methane is 86.

The diesel and gasoline extraction emission factors were obtained from Natural Resources Canada's GHGenius, 2004.[25] Propane was not included because the quantity used on-site is small and expected to have a negligible contribution, similar to gasoline. The coal extraction emission factor is based on Zhang and Mabee.

Table 5. Fuel extraction emissions

Fuel	CO_2e Emission factor	Units
Natural gas	4.46E-04	t/m^3
Diesel[26]	1.016	t/t
Gasoline[27]	1.059	t/t
Coal[28]	0.170	t/t

2.5 Fuel transport

Sources of fuel were provided by Lafarge. Distances were calculated using Google Maps. It was assumed that all fuel was transported to site by truck from Calgary. Transport emission factors for diesel trucks are the same as those presented in Section 1.6.3. Natural gas pipeline transport emissions are included in the natural gas extraction emission factor.

[24] IPCC, Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, *Climate Change 2014: Synthesis Report* (2014). http://www.ipcc.ch/report/ar5/syr/

[25] Natural Resources Canada, *GHGenius - A Model for Life Cycle Assessment of Transportation Fuels*, "GHGenius 3.2.xls" (2004),Table 54 'Upstream Results' worksheet.

[26] *GHGenius*.

[27] *GHGenius*.

[28] "Comparative study on the life-cycle greenhouse gas emissions of the utilization of potential low carbon fuels for the cement industry."

2.6 Site electricity

Electricity consumption data for Kiln 6 was provided by Lafarge. The emission factor for electricity from Alberta presented in Environment and Climate Change Canada 2018 National Inventory Report was used to calculate upstream emissions from electricity use on-site.[29] The GHG emission intensity of the Alberta grid was reported to be 0.9 tCO_2e/MWh in 2016. Electricity from Alberta has the highest GHG emissions intensity in Canada, because of the heavy reliance on coal and natural gas plants to generate power.

As stated by Lafarge, the electricity used for Kiln 6 is difficult to distinguish from total site electricity use, because it is not proportional to the clinker production. The finish grinding process required to produce cement from clinker accounts for 60–70% of site electricity use. As a result, there is a higher uncertainty associated with the emissions from electricity consumption for Kiln 6.

2.7 Clinker production

Kiln 6 produced 1,024,857 tonnes of clinker in 2017, accounting for 73% of the total clinker produced at the Exshaw cement plant. Clinker production emissions were provided by Lafarge and based on procedures and formulas outlined in the World Business Council for Sustainable Development guideline document.[30] Cement kiln dust is reused as an input and not sent to the landfill.

2.8 Fuel combustion

The kiln is fired using natural gas, alternative fuels or a mix of both. In addition, diesel, gasoline and propane are used to power equipment and vehicles on-site. Kiln and non-kiln fuel combustion emissions were provided by Lafarge.

All the alternative fuels included in this assessment have higher gross combustion emissions than natural gas because they are low-quality fuels with a higher ratio of carbon to hydrogen. However, for alternative fuels, only the non-biogenic fraction of

[29] Environment and Climate Change Canada, *National Inventory Report 1990 –2016: Greenhous Gas Sources and Sinks in Canada, Part 3* (2018). https://unfccc.int/documents/65715

[30] World Business Council for Sustainable Development Cement Sustainability Initiative, "CO2 and Energy Accounting and Reporting Standard for the Cement Industry (May 2011), Version 3.0, https://www.wbcsdcement.org/pdf/tf1_co2%20protocol%20v3.pdf

the fuel carbon was used to calculate the combustion GHG emissions. Intergovernmental Panel on Climate Change (IPCC) guidelines state that CO_2 emissions from biomass fuel combustion should not be included in national inventories because they are counted in the Agriculture, Forestry and Other Land-Use (AFOLU) sector.[31] Canadian guidelines delineate that CO_2 emissions from biomass combustion should be reported but not counted.[32] CO_2 emissions from biomass combustion considered to be carbon neutral if sustainable harvesting practices are used.[33] If the crop is regrown, it absorbs carbon from the atmosphere over the course of its lifetime, leading to a net balance of carbon in the system. Recently, several studies have challenged the carbon neutrality of biomass combustion and suggest burning biomass actually creates a "carbon debt."[34,35,36]

A recent study from the Laurentian Forestry Centre in Québec investigated the GHG emissions from biomass combustion for a variety of scenarios.[37] The results are dependent on the feedstock, end use (heat or electricity), the fuel that is replaced (coal, natural gas, or oil), and the time frame under consideration. The study examines a multitude of scenarios based on these variables. The scenario most comparable to using waste fuels for kiln combustion is harvest residue replacing natural gas used for heating. The results for this scenario show carbon neutrality is achieved after anywhere from 27 to 67 years, with the harvest residue emitting more CO_2 before the breakeven point and less CO_2 after. This indicates time frame is an important parameter. The time delay in the combustion of the waste fuels due to their use as a commodity prior to burning is likely to improve their carbon footprint. However, this will depend on variable specific

[31] Dario Gomez et al, "IPCC Guidelines for national greenhouse gas inventories (2006), Chapter 2: Stationary Combustion", Intergovernmental Panel on Climate Change, 2.33, http://www.ipcc-nggip.iges.or.jp/public/2006gl

[32] Environment and Climate Change Canada, "Technical Guidance on Reporting Greenhouse Gas Emissions (2016)," 10, http://publications.gc.ca/collections/collection_2016/eccc/En81-6-2016-eng.pdf

[33] A. J. Ragauskas, et al., "The Path Forward for Biofuels and Biomaterials" *Science* 311 (2006). DOI: 10.1126/science.1114736

[34] Weiguo Liu et al, Analysis of the Global Warming Potential of Biogenic CO_2 Emission in Life Cycle Assessments. Scientific Reports, 7 (2017).

[35] European Academies Science Advisory Council , "Multi-functionality and sustainability in the European Union's forests (2017)", https://www.easac.eu/fileadmin/PDF_s/reports_statements/Forests/EASAC_Forests_web_complete.pdf

[36] Kim Pingoud et al, "Global warming potential factors and warming payback time as climate indicators of forest biomass use," *Springer Nature*, 2011. https://link.springer.com/article/10.1007/s11027-011-9331-9

[37] Jérôme Laganière et al, "Range and uncertainties in estimating delays in greenhouse gas mitigation potential of forest bioenergy sourced from Canadian forests," 9, no. 2, (2015), https://onlinelibrary.wiley.com/doi/full/10.1111/gcbb.12327

to each fuel, including their expected lifetime prior to being used as a combustion fuel, the percentage of biogenic carbon, and the fuel feedstock. Further analysis on this issue is recommended, potentially using the model developed by the Laurentian Forestry Centre.

2.9 Alternative kiln fuels

All the alternative fuels, or low-carbon fuels, are assumed to be waste materials with no associated production emissions. It was assumed all alternative fuels would be sourced from Calgary and transported to site by diesel truck. The fuels require processing prior to use. Alternative fuel processing emissions were calculated based on methodology from Zhang and Mabee. Railway ties require only crushing while all other alternative fuels require crushing, sorting and pre-treatment. Alternative fuel heating values and combustion emission factors were provided by Lafarge. The mass of each alternative fuel required to generate the same amount of heat in the kiln was calculated based on heating values and a natural gas density provided by Lafarge. Kiln fuel properties including the heating value, emission factors and biogenic carbon percentage are presented in Table 6. Alternative fuels' properties provided by Lafarge were sourced from similar projects and do not necessarily represent those of fuels available in the Calgary region.[38] Methane (CH_4) and nitrous oxide (N_2O) emissions were not provided by Lafarge, but are deemed small compared to those of CO_2 and well within the uncertainty of the CO_2 emission factors for alternative fuels.

Table 6. Kiln fuel properties

Fuel	Lower heating value (GJ/tonne)	CO_2 emission factor (kg/kg)	Non-biogenic CO_2 emission factor (kg/kg)	Biogenic carbon (%)
Coal	24.9	2.41	2.41	0%
Natural gas	43.0	2.41	2.41	0%
Plastics (HDPE, LDPE, PP)	44.3	3.14	3.14	0%
Tire fluff	37.7	3.07	2.21	28%

[38] As part of its mandate in this project, the University of Calgary has hired a consulting company to conduct a proper characterization of alternative fuels available in the Calgary region. Pembina recommends this life cycle analysis be updated with these properties once available.

Rubber	31.2	2.40	1.92	20%
Carpet	18.5	1.86	1.86	0%
Shingles	17.5	1.62	1.29	20%
Railway ties	17.3	1.43	0.37	74%
Construction and demolition waste	17.5	1.71	0.02	99%
Wood	17.2	1.67	0.00	100%
Textiles (natural)	14.2	2.26	0.00	100%

Source: Lafarge

A combination of alternative fuels proposed by Lafarge was also evaluated.[39] This fuel comprises 50% natural gas and a number of other waste fuels as outlined below:

- 50% natural gas
- 10% railway ties
- 25% construction and demolition waste
- 7% shingles
- 2.5% tire fluff
- 1% textiles
- 5% plastics

Table 7. Alternative fuel processing emission factors

Activity	CO_2e emission factor (t/t)
Crushing	0.021
Crushing and sorting	0.018

Source: Zhang and Mabee

2.10 Landfilling

Landfilling is included in this study to estimate the potential indirect GHG savings from diverting waste materials destined for the landfill for use as kiln fuel in clinker production. At a landfill, these waste materials decompose anaerobically and release

[39] *Assessing the role of low carbon fuels in reducing carbon emissions from cement plants.*

methane, carbon dioxide and other gases. Landfilling emissions include the methane release from the decomposition of the waste and the emissions to transport the material to a landfill in Calgary.

There are many approaches to estimating the methane emissions from landfill waste. The method recommended by the British Columbia Ministry of Environment[40] and used by Zhang and Mabee was applied here. Waste materials are separated into three categories based on their organic matter content: relatively inert, moderately decomposable and decomposable. The methane generation potentials of these three categories are respectively 20, 120, and 160 m^3/t.

Methane generation at landfills is typically modelled using first order kinetics and depends on the composition of the waste along with site conditions like temperature, moisture content, pH and nutrient availability.[41] Over 80% of the total methane is released within the first 40 years.[42,43,44] The assessment conducted here is a simplified approach that doesn't account for the time frame of methane generation at landfills. In addition, at some landfills methane is captured and either flared or used to generate electricity, thus reducing the impact of landfilling waste on GHG emissions. In 2015, around 1/3 of landfill gas was captured in Canada.[45] However, methane capture or flaring isn't considered in this assessment.

The GHG emissions from transporting the waste to landfill were negligible compared to the GHG generated during landfilling. To provide a conservative estimate of the transport emissions a transport distance of 15 km was used. This is approximately the maximum distance from any point in Calgary to a landfill, as calculated using Google Maps.

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[40] British Columbia Ministry of Environment, *Landfill Gas Generation Assessment Procedure Guidelines* (2009), Appendix A. https://www2.gov.bc.ca/gov/content/environment/waste-management/garbage/landfills

[41] Ibid.

[42] A. Damgaard et al., "LCA and economic evaluation of landfill leachate and gas technologies," *Waste Management*, 31, no. 7 (2011), 1532.

[43] A. Niskanen, S. Manfredi, T.H. Christensen, R. Anderson, "Environmental assessment of Ammassuo landfill (Finland) by means of LCA-modelling (EASEWASTE)," *Waste Management and Research*. 27, no. 5 (2009), 542.

[44] G. Obersteiner, E. Binner, P. Mostbauer, S. Salhofer, "Landfill modelling in LCA - a contribution based on empirical data" *Waste Management*, 27, no. 8 (2007), S58.

[45] Environment and Climate Change Canada, "Municipal Solid Waste and Greenhouse Gases," August 16, 2018, http://www.ec.gc.ca/gdd-mw/default.asp?lang=En&n=6f92e701-1&wbdisable=true

A global warming potential (GWP) for methane of 28 was used to convert methane emissions to carbon dioxide equivalent, based on the IPCC fifth assessment report[46] This is a conservative estimate because it is based on a 100-year time frame, while methane emissions typically stay in the atmosphere for around a decade. On a 20-year time frame, the GWP of methane is 86. Due to its short lifetime, methane has a large immediate impact on the climate.

Table 8. Kiln fuel landfill methane generation potential

Fuel	CO_2e emission factor (t/t)
Construction and demolition waste	2.35
Shingles	0.39
Plastics (HDPE, LDPE, PP)	0.39
Railway ties	2.35
Wood	2.35
Rubber	0.39
Tire fluff	0.39
Carpet	0.39
Textiles (natural)	2.35

Source: BC Ministry of Environment

[46] *Climate Change 2014: Synthesis Report*.

3. Results

This section presents and discusses the main results from the LCA of greenhouse gas emissions. Full results are available in the spreadsheet developed to conduct the analysis.

3.1 Baseline scenario

Table 9 shows the distribution of GHG emissions for the baseline fuel scenario — that is, with the kiln running exclusively on natural gas. These values are presented graphically in Figure 2. Emissions are presented per tonne of clinker produced and are primarily generated in the kiln through the calcination process and the combustion of kiln fuel. The use of alternative kiln fuels only has an impact on the kiln fuel combustion, extraction and transport emissions. These emissions account for 25% of the life cycle GHG emissions from producing clinker in Kiln 6. This value represents the upper limit of potential GHG reductions from replacing natural gas with lower carbon kiln fuels.

Table 9. Breakdown of GHG emissions from baseline fuel scenario

Source	Affected by alternative kiln fuel use	CO_2e emissions (% of total)	CO_2e emissions (t/t clinker)
Calcination	No	61%	540
Kiln fuel combustion	Yes	21%	183
Raw material extraction and transport	No	8%	70
Site electricity	No	5%	40
Kiln fuel extraction, transport	Yes	5%	40
Diesel, gasoline, and propane extraction, transport, and combustion	No	1%	6
Total		**100%**	**880**

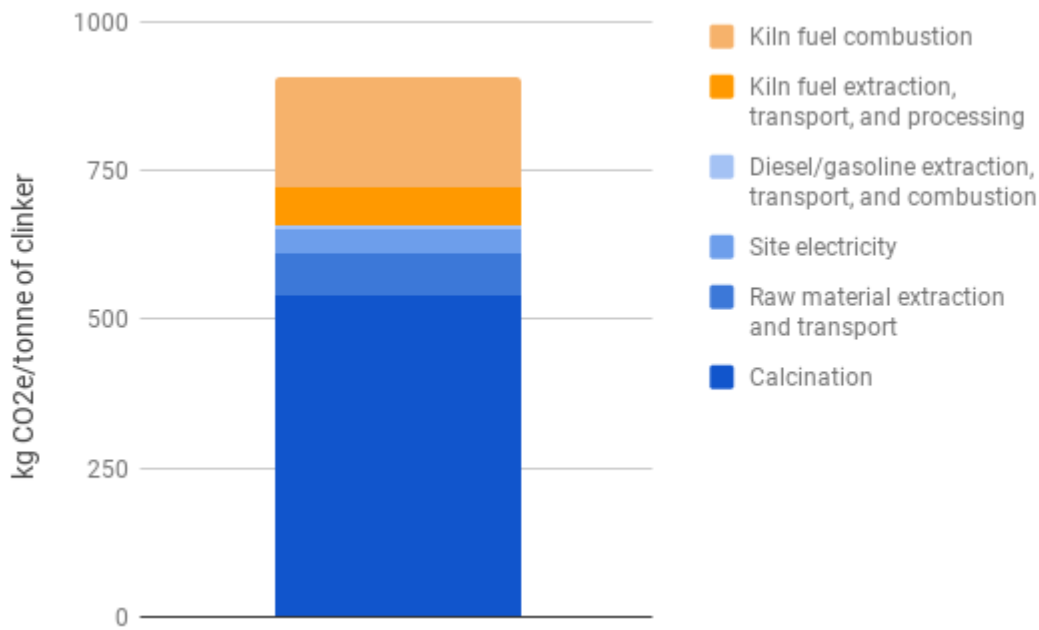

Figure 2. Breakdown of life cycle GHG emissions per tonne of clinker for baseline scenario

The majority of emissions are from the calcination process. Emissions from the combustion of kiln fuel (natural gas) are also significant, but lower than for typical cement operations. This is due to the use of natural gas at the Exshaw facility instead of coal (or coke), which is typically used in cement kilns across the world. The GHG emissions of natural gas are significantly lower than those of coal.

Raw material extraction and transport is a minor contributor. Limestone accounts for close to 80% of the primary raw material used in the manufacture of clinker and 95% of raw material extraction emissions. Raw material transport emissions are an even smaller contributor than extraction. Bottom ash is the main source of raw material transport emissions due to the significant quantity used in clinker production, long transport distance, and high impact transport method (truck).

Electricity is another minor contributor, but higher than for most cement plants, because a significant fraction of Alberta's electricity grid comes from coal and natural gas plants, leading to a high emission intensity for the Alberta grid.

Kiln fuel extraction, transport, and processing are also a small contributor to total emissions. Natural gas life cycle GHG emissions come from carbon dioxide generated from stationary combustion and electricity used in production, processing and transmission, along with methane released through venting and fugitive emissions.

Emissions from the extraction, transport, and combustion of non-kiln fuels (diesel, gasoline, and propane) are insignificant. These fuels are used to operate vehicles and equipment on-site.

3.2 Alternative fuel scenario, 100% substitution rate

Figure 3 shows life cycle GHG emissions assuming that 100% of the base fuel used to fire the kiln (natural gas) is replaced with the alternative fuel listed. Emissions are presented per tonne of clinker produced. Coal is included for comparison because it is a commonly used kiln fuel. The GHG emissions shown here represent the maximum achievable GHG reductions (or, in some cases, excess) for each alternative fuel.

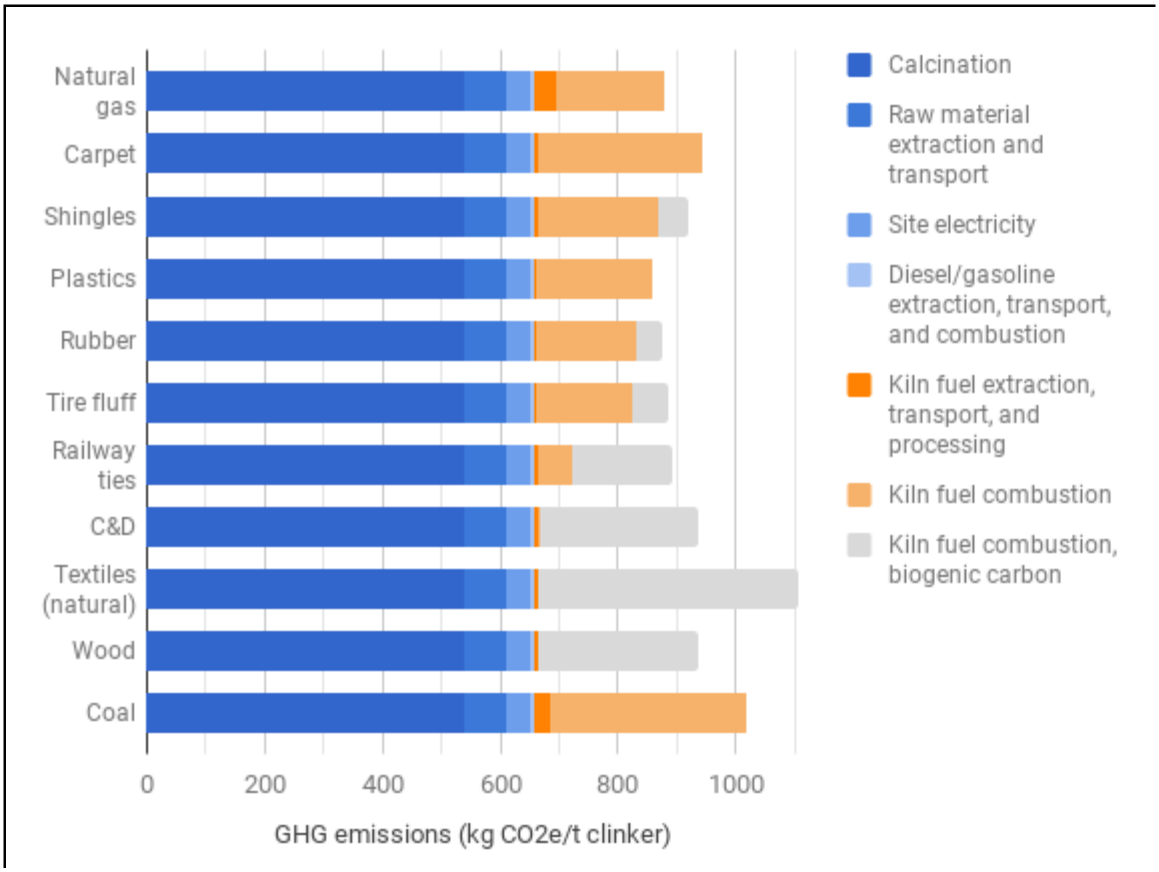

Figure 3. Comparison of GHG emissions per tonne of clinker for natural gas, coal, and alternative fuels assuming a 100% fuel substitution rate

Construction and demolition waste, wood and natural textiles show the greatest reduction in emissions intensity, at 24–25%. Railway ties are not far off at 18%.

Meanwhile shingles, plastics, rubber and tire fluff are in another tier with emissions intensities that are 1–7% lower than natural gas. Carpet on the other hand is 7% worse than natural gas. Coal, in comparison, has an emissions intensity 15% higher than that of natural gas.

As expected, the main impact of fuel substitution on the total emissions is in the kiln fuel combustion category. There is also a reduction in the GHG emissions from kiln fuel extraction, transport, and processing emissions because the alternative fuels are waste products and would have been sent to the landfill if they were not used as waste fuels. A small amount of energy is required to sort, crush and transport the waste fuels, but the emissions from these sources are insignificant. The impact of this category depends on the leak rate and GWP assumed for methane. These factors are investigated in more detail in Section 3.4.

The kiln fuel combustion emissions shown in Figure 3 exclude the biogenic carbon portion of the fuel. The biogenic carbon emissions are shown in gray for reference. All the alternative fuels have higher gross combustion emissions than natural gas because they are low-quality fuels with a higher ratio of carbon to hydrogen. However, only the non-biogenic fraction of the combustion emissions are assumed to contribute to climate change. As a result, the alternative fuels such as construction and demolition waste, railway ties, wood, and natural textiles which have a high fraction of biogenic carbon have lower combustion emissions. Similarly, fuels that are primarily derived from fossil carbon — shingles, plastics, rubber, tire fluff and carpet — have total GHG emissions that are comparable to those of natural gas.

Figure 4 presents the life cycle GHG emissions of the alternative fuels and coal relative to natural gas on a percent basis. Emissions shown in this figure exclude biogenic carbon emissions.

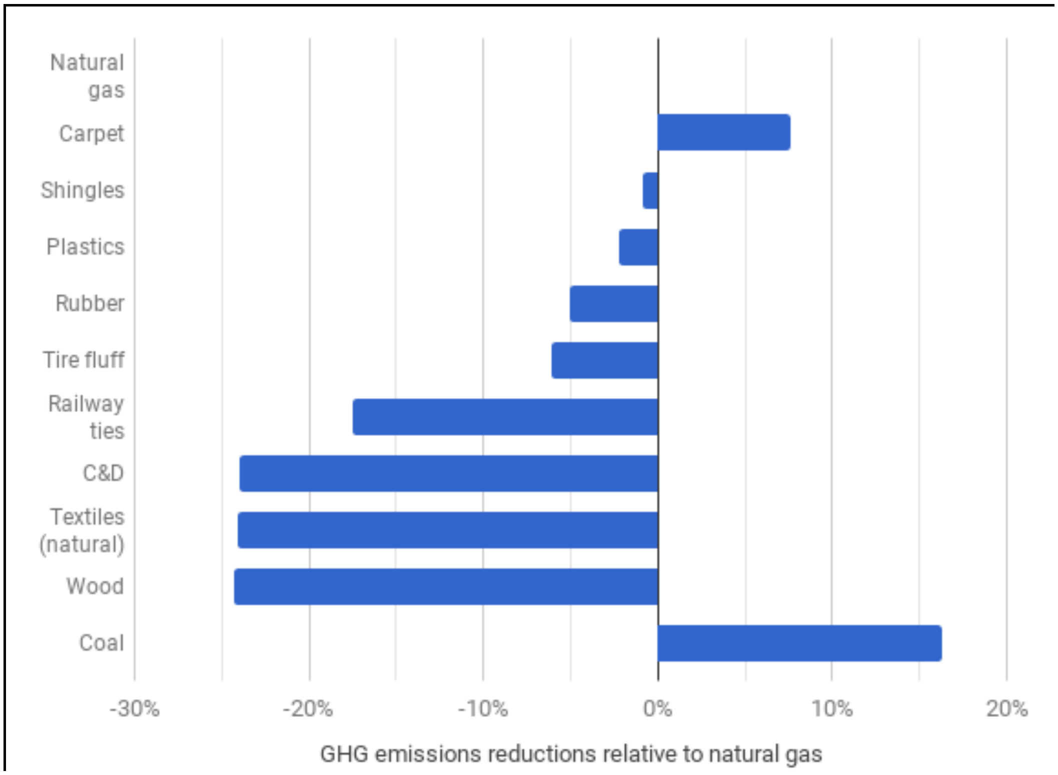

Figure 4. Comparison of GHG emissions per tonne of clinker of coal and alternative fuels against natural gas assuming a 100% fuel substitution rate

3.2.1 Accounting for landfill emissions

An additional pathway that was evaluated was the impact of diverting waste from the landfill for use as kiln fuel. Waste that is sent to a landfill can decompose and generate methane, which is a much more potent GHG than carbon dioxide. Figure 5 compares the total GHG emissions and avoided landfill emissions for all fuels considered (assuming 100% of that fuel is used for kiln). The fuels that have the highest potential for avoided landfill emissions are those that have a high biogenic carbon content and decompose in the landfill: construction and demolition waste, railway ties, wood and natural textiles. These are also the fuels with the lowest life cycle GHG emissions. The avoided landfill emissions from these fuels are over half of their life cycle GHG emissions. The remaining fuels all have low biogenic carbon content and are manufactured from fossil fuels. Their avoided landfill emissions are low compared to their life cycle GHG emissions.

It should be emphasized that the time frame of landfill emissions differs from the time frame of all other life cycle emissions. Landfill methane is released over 40 years or more while emissions from fuel combustion and clinker production are instantaneous.

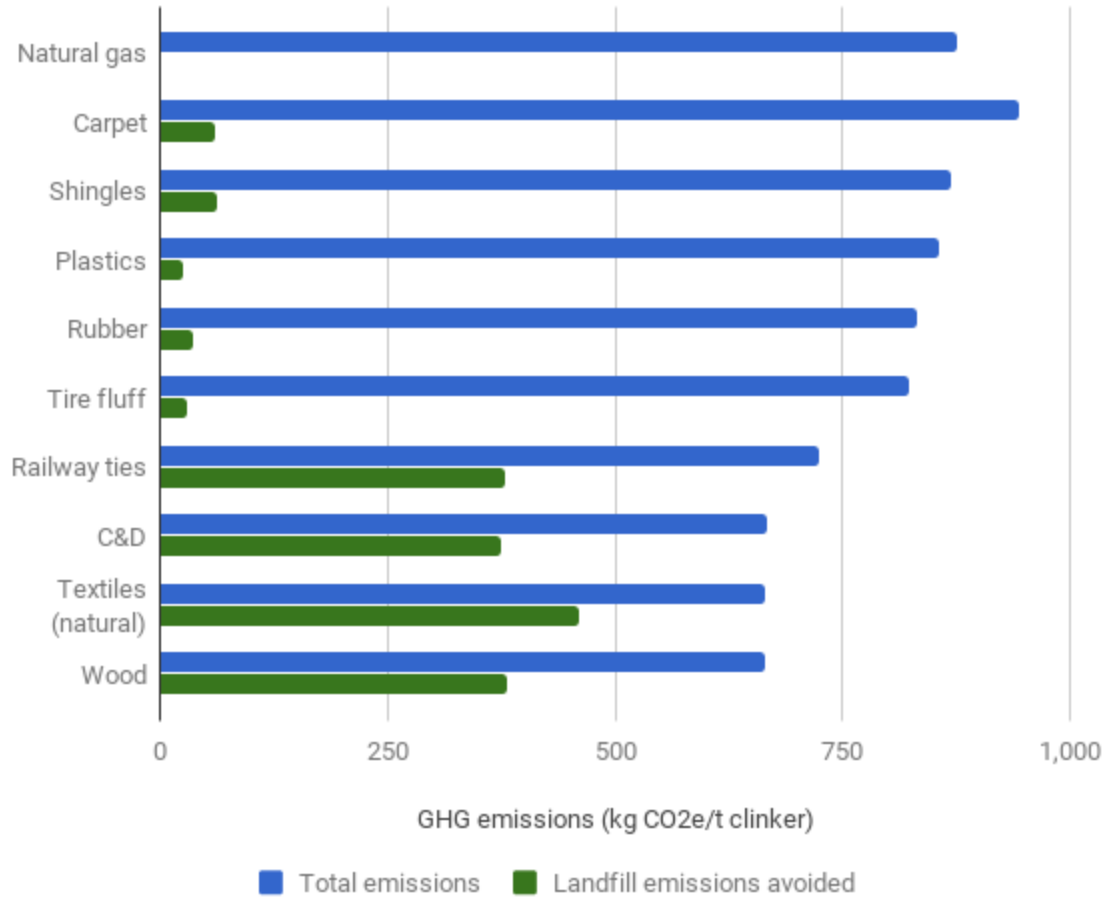

Figure 5. Total GHG emissions per tonne of clinker and avoided landfill emissions for natural gas and alternative fuels assuming a 100% fuel substitution rate

3.3 Alternative fuel scenario, 50% substitution rate

Figure 6 and Figure 7 compare the life cycle GHG emissions for natural gas and the nine alternative fuels assuming a 50% fuel substitution rate on an absolute and relative basis, respectively. The mixture of natural gas and waste fuels proposed by Lafarge was also included here, because it assumes a 50% substitution rate. Construction and demolition waste, wood, railway ties and natural textiles show the greatest potential for reducing GHG emissions with reductions in the range of 9–12%. Shingles, plastics, rubber, carpet and tire fluff only reduce the GHG emissions intensity by 1–3%.

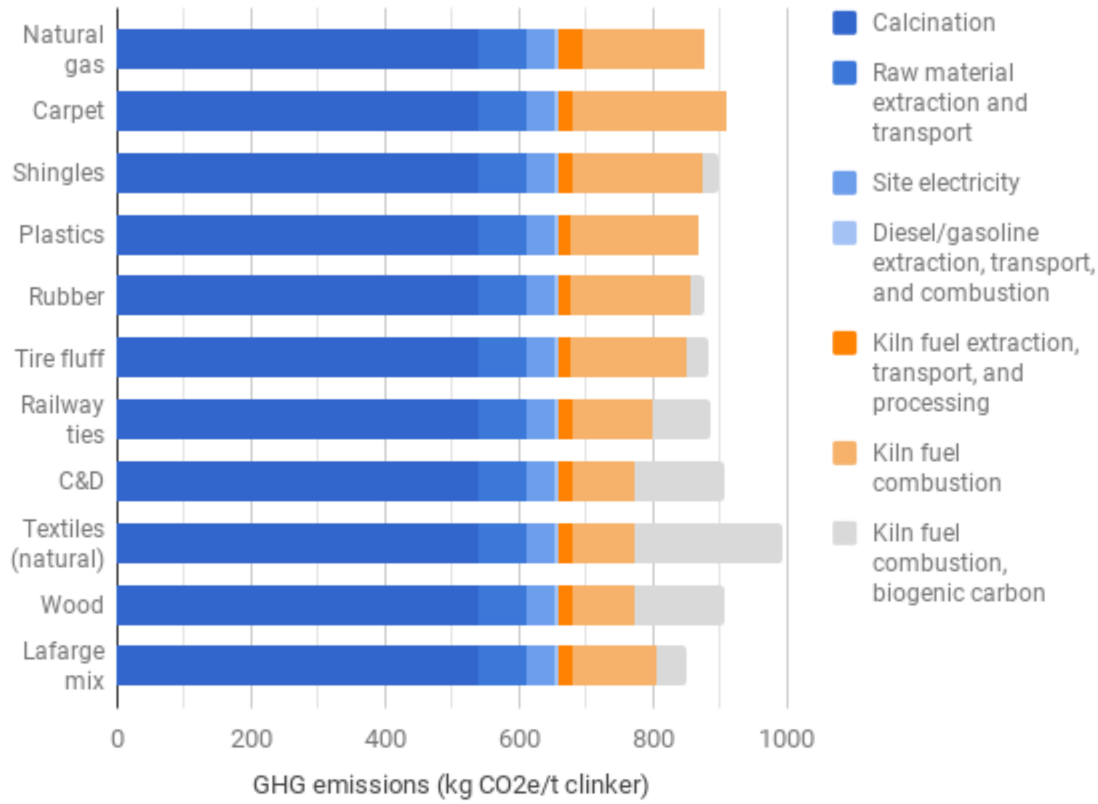

Figure 6. Comparison of GHG emissions per tonne of clinker for natural gas and alternative fuels assuming a 50% fuel substitution rate

Note: The composition of the "Lafarge mix" is outlined in section 2.9.

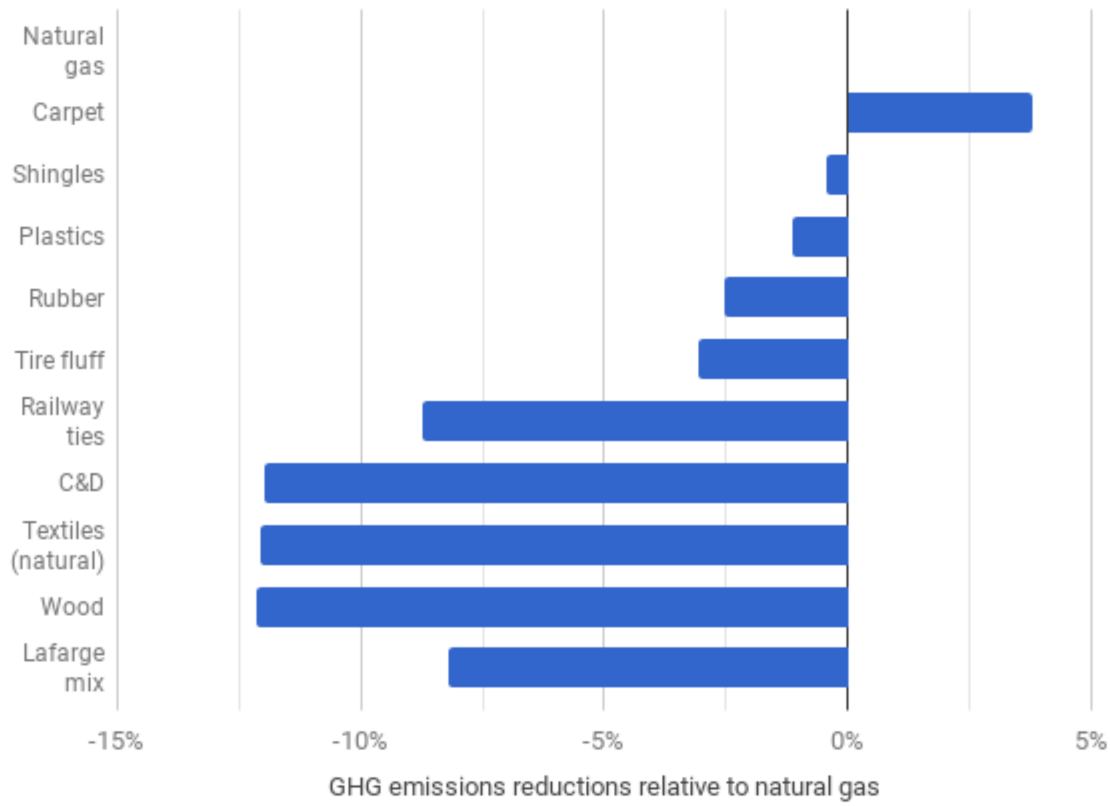

Figure 7. Comparison of GHG emissions per tonne of clinker of coal and alternative fuels against natural gas assuming a 50% fuel substitution rate

3.3.1 Accounting for landfill emissions

Figure 8 shows a comparison of total GHG emissions and avoided landfill emissions for all fuels under consideration assuming a 50% fuel substitution rate. The avoided landfill emissions are half of what they were for the 100% fuel substitution scenario.

It should again be emphasized that the time frame of landfill emissions differs from the time frame of all other life cycle emissions. Landfill methane is released over 40 years or more while emissions from fuel combustion and clinker production are instantaneous.

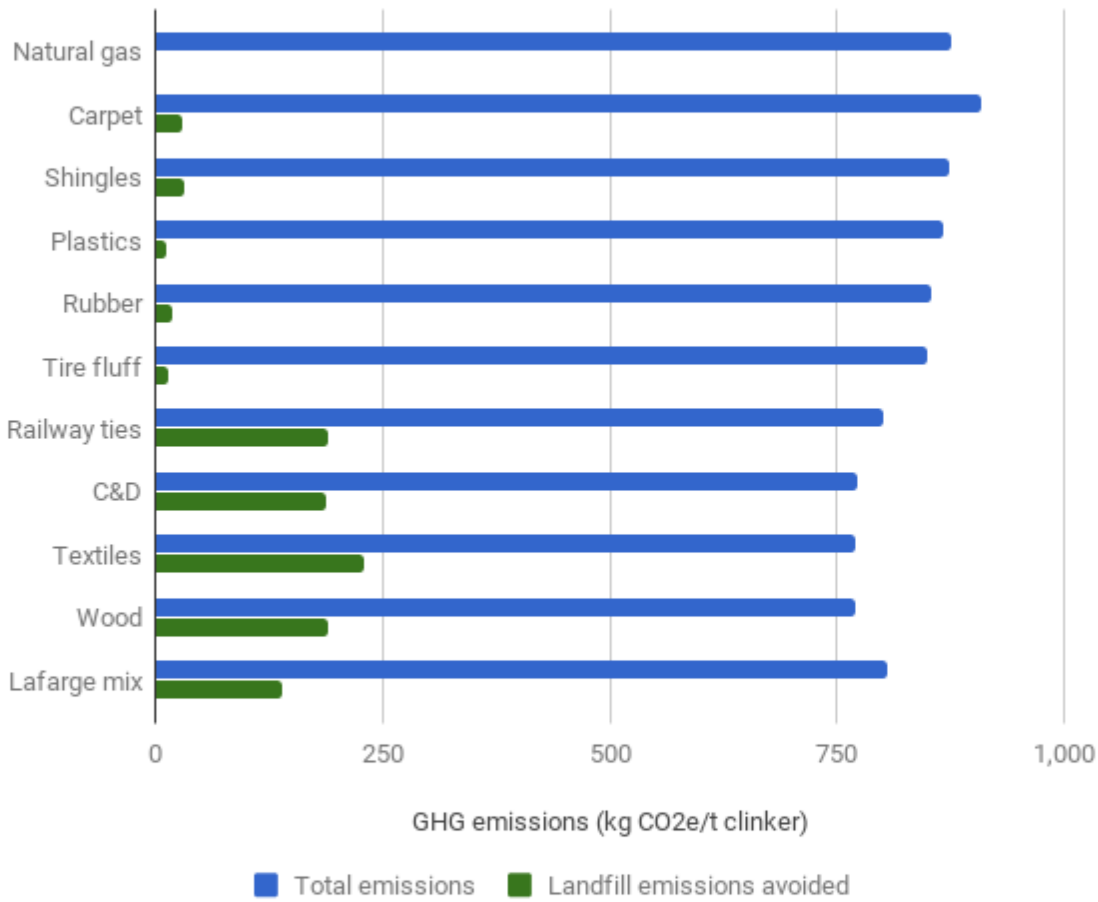

Figure 8. Total GHG emissions per tonne of clinker and avoided landfill emissions for natural gas and alternative fuels assuming a 50% fuel substitution rate.

3.4 Sensitivity analysis

An analysis of the sensitivity of the results to a variation in the methane leak rate and methane global warming potential was conducted for natural gas and the Lafarge fuel mix.[47] Figure 9 shows the sensitivity of the GHG emissions per tonne of clinker to methane leak rate and GWP for natural gas and the Lafarge fuel mix. Figure 10 shows the impact of methane leak rate and GWP on the GHG reductions expected when switching from natural gas to the Lafarge fuel mix. The life cycle GHG emissions from the Lafarge mix are similar to those of railway ties at a 50% substitution rate. For the

[47] This fuel mix is composed of 50% of natural gas and 50% of a mix of alternative fuels. The exact composition of the mix is outlined in section 2.9,

sensitivity analysis, a range of methane leak rates from 0% to 3% were considered along with two GWP values for methane based on 100 and 20 year time frame presented in the IPCC's fifth assessment report (the GWP values are 28 and 86 respectively).[48] For context, two ranges of methane leak rates are highlighted in the figures below based on recent studies estimating the degree of underreporting of methane emissions from oil and gas operations in Canada[49] and the United States.[50] For reference, a leak rate of 0.7% (as calculated based on Canada's 2018 National Inventory Report) and methane GWP of 28 were used in the present study.

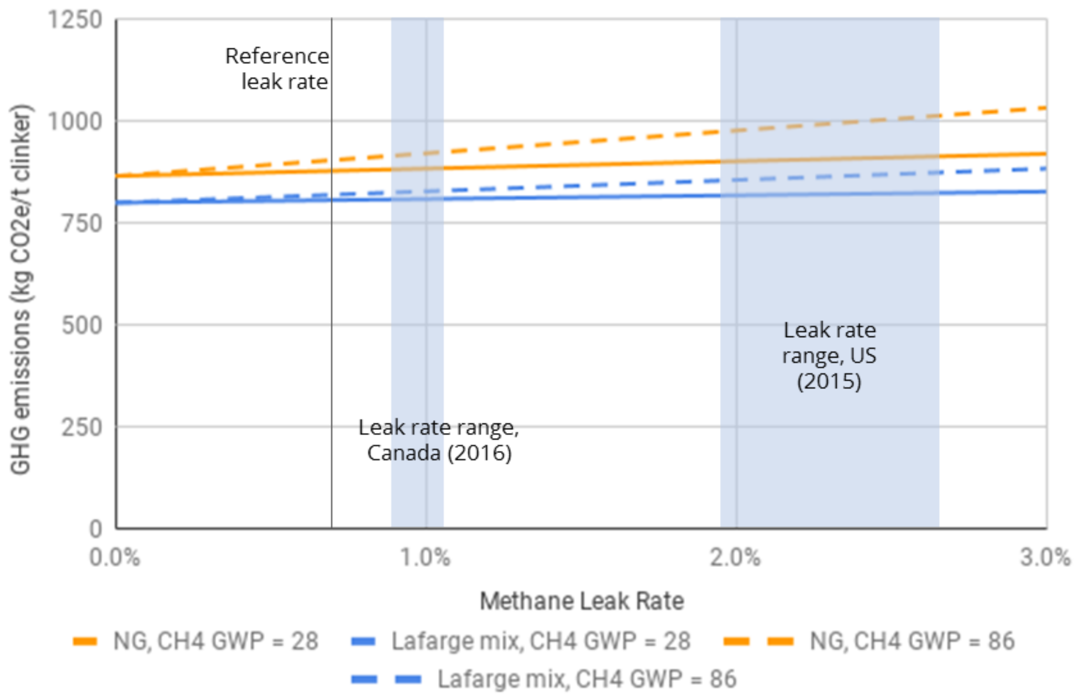

Figure 9. Variation in total GHG emissions per tonne of clinker for natural gas and the Lafarge fuel mix with methane leak rate for 20 and 100-year methane GWPs.

A higher leak rate or a higher GWP of methane individually don't have a large impact on the expected GHG reductions. However considering both a higher leak rate and a larger GWP, the impact on GHG reductions achieved by switching the Lafarge fuel mix is noticeable (close to 5 percentage points when using a GWP of 28 and a leak rate

[48] IPCC, Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, *Climate Change 2014: Synthesis Report* (2014). http://www.ipcc.ch/report/ar5/syr/

[49] "Assessment of methane emissions from the U.S. oil and gas supply chain."

[50] "Comparisons of Airborne Measurements and Inventory Estimates of Methane Emissions in the Alberta Upstream Oil and Gas Sector."

equivalent to the estimated U.S. average of 2.3%). This analysis was not propagated to the landfill scenario because the landfill emissions are an estimate and do not consider the time frames of methane release.

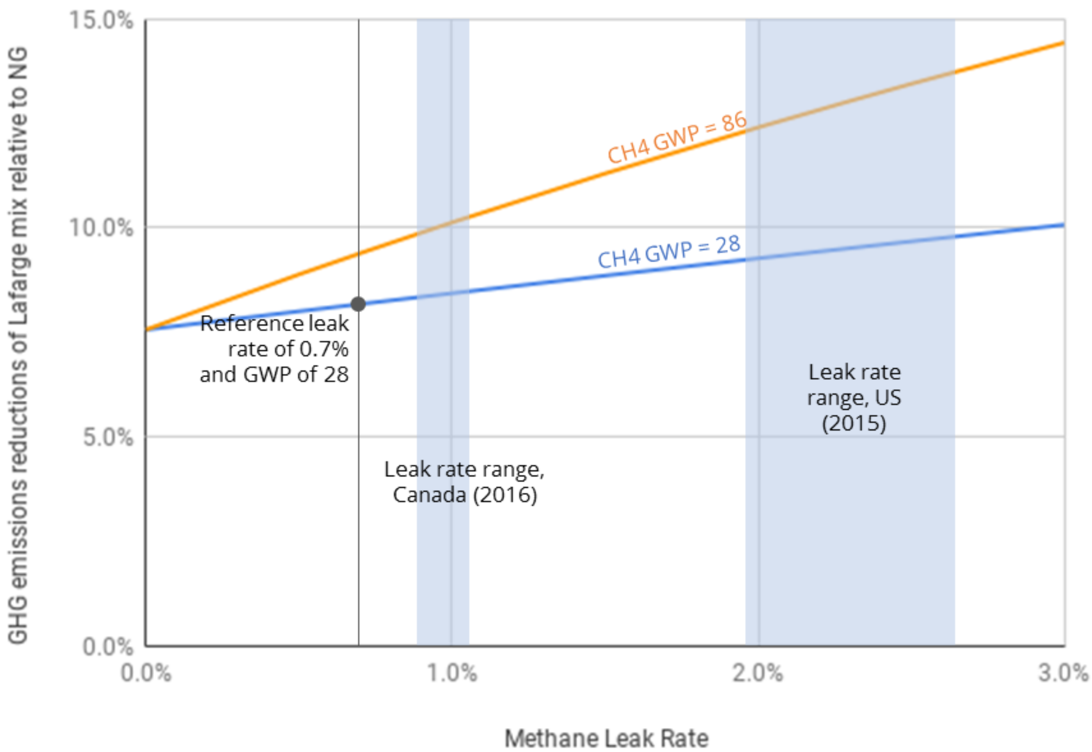

Figure 10. Trend in life cycle GHG reduction per tonne of clinker for the Lafarge fuel mix relative to natural gas with a varying methane leak rate for 20 and 100-year methane GWPs.

4. Conclusions

An LCA of GHG emissions from the production of clinker at Kiln 6 of the Lafarge cement plant was performed. Nine alternative fuels were considered for use in displacing natural gas. In the business-as-usual scenario, the kiln is fired with natural gas only. Two additional scenarios were considered using a natural gas substitution rate of 50% and 100%. In addition, the emissions avoided by diverting waste from the landfill were also calculated. Finally, a sensitivity analysis was conducted to determine the effect of the methane leak rate and GWP on the results using the fuel mix proposed by Lafarge.

Fuels composed primarily of biogenic carbon showed the most promising reductions in GHGs, mostly because of the assumptions inherent to carbon accounting. Although these fuels emit more GHGs per tonne of clinker, the combustion emissions that stem from biogenic carbon are not counted because they are considered to be a part of the natural carbon cycle and thus carbon neutral. These fuels include construction and demolition waste, railway ties, wood, and natural textiles. With a 50% substitution rate, these fuels have the potential to reduce GHG emissions by 9–12%. For comparison, the Lafarge fuel mix shows a reduction of 8%.

Similarly, the fuels composed of biogenic matter showed the highest avoided landfill emissions. The best alternative fuels avoided landfill emissions in the range of 21–26% of total GHG emissions for the baseline natural gas scenario assuming a 50% substitution rate. For comparison, the avoided landfill emissions of the Lafarge fuel mix are 16% of total GHG emissions for the baseline natural gas scenario.

The methane leak rate and GWP used have a significant impact on the expected GHG reductions from the use of alternative fuels in the kiln. The GHG emissions reductions for the Lafarge fuel mix increase from 8.2 to 13.0% when a methane leak rate of 2.3% and methane GWP of 86 are used. The 2.3% methane leak rate is the most recent estimate based on studies conducted in the United States.[51]

[51] "Assessment of methane emissions from the U.S. oil and gas supply chain"

5. Recommendations

In the next phase of this project, the University of Calgary will be investigating the life cycle GHG emissions in more details. The Pembina Institute recommends exploring some or all of the following:

- Update the alternative fuel properties with those from the study characterizing alternative fuels available in the Calgary region[52]
- Determine landfill methane generation from waste materials more accurately using a first order model
- Evaluate the amount of methane capture currently occurring at Calgary and Alberta landfills and use this to add additional landfill scenarios that assume some methane is captured
- Reconcile the time frames of different parts of the model, including the methane emissions GWP and the landfill emissions
- Further analyze the carbon neutrality of biomass fuels, potentially using the method developed by the Laurentian Forestry Centre[53]
- Examine uncertainties of waste fuel combustion emission factors.

[52] Alternative fuels' properties used in this analysis were sourced from similar projects and are not specific to the Calgary context. As part of its mandate in this project, the University of Calgary has hired a consulting company to conduct a characterization of alternative fuels available in the Calgary region.

[53] Laganière et al, "Range and uncertainties in estimating delays in greenhouse gas mitigation potential of forest bioenergy sourced from Canadian forests," 9.

Appendix A. Data tables

Table 10 and Table 11 present the life cycle GHG emissions by category for all fuels included in this assessment assuming a 100% and 50% fuel substitution rate, respectively.

Table 10. Life cycle GHG emissions for all fuels assuming 100% substitution rate

Fuel	Emissions (kg CO_2e/t clinker)								Difference Relative to NG
	Calcination	Raw material extraction and transport	Site electricity	Diesel/gasoline extraction, transport, and combustion	Kiln fuel extraction, transport, and processing	Kiln fuel combustion	Landfill emissions avoided	Total emissions	
Natural gas	540	71	40	6	36	183	-	877	–
Carpet	540	71	40	6	6	279	59	943	4%
Shingles	540	71	40	6	7	205	63	869	-4%
Plastics	540	71	40	6	3	197	25	857	-5%
Rubber	540	71	40	6	4	171	35	832	-8%
Tire fluff	540	71	40	6	3	163	29	823	-9%
Railway ties	540	71	40	6	6	60	378	723	-20%
C&D	540	71	40	6	7	3	374	667	-26%
Textiles (natural)	540	71	40	6	8	0	461	666	-27%
Wood	540	71	40	6	7	0	381	664	-27%
Coal	540	71	40	6	27	335	-	1,019	13%

Table 11. Life cycle GHG emissions for all fuels assuming 50% substitution rate

Fuel	Emissions (kg CO_2e/t clinker)								Difference Relative to NG
	Calcination	Raw material extraction and transport	Site electricity	Diesel/gasoline extraction, transport, and combustion	Kiln fuel extraction, transport, and processing	Kiln fuel combustion	Landfill emissions avoided	Total emissions	
Natural gas	540	71	40	6	36	183		877	-
Carpet	540	71	40	6	21	231	30	910	4%
Shingles	540	71	40	6	21	194	31	873	0%
Plastics	540	71	40	6	19	190	12	867	-1%
Rubber	540	71	40	6	20	177	18	854	-3%
Tire fluff	540	71	40	6	20	173	15	850	-3%
Railway ties	540	71	40	6	21	121	189	800	-9%
C&D	540	71	40	6	21	93	187	772	-12%
Textiles (natural)	540	71	40	6	22	91	230	771	-12%
Wood	540	71	40	6	22	91	190	770	-12%
Lafarge mix	540	71	40	6	21	126	140	805	-8%

Appendix B. Natural gas life cycle GHG emissions

Life cycle GHG emissions for natural gas in Canada were calculated using data from the 2018 National Inventory Report (NIR)[54] and are presented in Table 12. The results are based on 2016 data. Stationary combustion emissions for natural gas production and processing are obtained from Table A10-3. Fugitives, venting, flaring and transport emissions are obtained from the 2018 CRF tables for 2016.[55] The total GHG emissions from natural gas production, processing, transmission, and distribution are 62.0 Mt CO_2e.

The total marketable natural gas production in Canada was 158 billion m^3 in 2016.[56] This results in an upstream natural gas emission factor of 0.393 kg CO_2e/m^3 of natural gas. To calculate methane emissions as a percent of total production, only the methane emissions from fugitives and venting were considered. Methane emissions from stationary combustion, transport and flaring are typically due to incomplete combustion and are consequently not included in calculation of the methane leak rate. The calculated leak rate is 0.70% of total production.

[54] *National Inventory Report 1990–2016, Part 3.*

[55] Ibid

[56] NEB, "Marketable Natural Gas Production in Canada, 2017," updated March 15, 2018. https://www.neb-one.gc.ca/nrg/sttstc/ntrlgs/stt/mrktblntrlgsprdctn-eng.html

Table 12. Natural gas life cycle emissions

Source	CO_2 Emissions (kt)	CH_4 Emissions (kt)	CH_4 Emissions (kt CO_2e)[a]
Stationary combustion[b]	27,000.0	-	-
Transport	8,114.0	8.1	227.4
Fugitives			
a) Exploration	-	-	-
b) Production	2.6	92.8	2,597.3
c) Processing	7.7	10.9	305.8
d) Transmission and storage	38.6	46.9	1,314.3
e) Distribution	2.0	38.2	1,069.9
f) Other	55.7	286.5	8,022.3
Venting	3,857.8	299.4	8,382.6
Flaring	892.4	5.4	150.4
Total	**39,970.8**	**788.2**	**22,069.9**

[a] 100-year time horizon global warming potentials from the IPCC's Fifth Assessment Report are used.

[b] Stationary combustion emissions are presented as total GHG emissions and not separated into CO_2, CH_4, and N_2O.

Appendix C. Summary of life cycle activities and data sources

Table 13 and Table 14 summarize the life cycle activity data and data sources for all segments of the life cycle.

Table 13. List of activities and description

Activity	Description
Raw material extraction	• Limestone is quarried on-site with diesel-powered equipment • A loader and portable drill are used at the Seebe and Yamnuska quarries to extract shale and sandstone, respectively • Black shale and pit run sourced from South Seebe quarry • Sandstone is sourced from the Yamnuska quarry • Iron, bottom ash, and sand are sourced from third party suppliers and considered to be waste products that would otherwise require disposal • Soil has negligible extraction emissions • Red shale and lime are purchased from third party suppliers
Raw material transport	• Limestone and soils are transported 1 km by truck • Black shale, sandstone, and pit run are transported 11 km by truck • Iron is sourced from various suppliers and transported 400–1500 km by truck or by rail • Bottom ash is transported 440 km by truck • Red shale is transported 650 km by rail • Lime is transported 11 km by truck • Sand is transported 176 km by truck
Fuel extraction	• Coal is surface mined and sourced from Fernie • Natural gas is produced and treated in Alberta • Oil is produced and refined into diesel and gasoline
Fuel transport	• Natural gas is transported 50 km by pipeline • Diesel and gasoline are transported 104 km by truck from Calgary • Coal is transported 349 km by truck • Alternative fuels sourced from Calgary are transported 100 km by truck
Alternative fuel processing	• Railway ties require only crushing; all other alternative fuels requires crushing, sorting, and pre-treatment
Site electricity	• Electricity is purchased from the Alberta grid
Plant operation	• Natural gas is combusted on-site as the primary fuel for the plant • Diesel along with a small amount of gasoline and propane are consumed on-site to operate equipment and vehicles • A small amount of natural gas is used to dry the raw materials • Maintain plant, equipment and vehicles • Alternative fuels are sourced from Calgary and transported 100 km to Exshaw
Landfill emissions	• Alternative fuels would be transported 15 km to a landfill in Calgary if they were not used on-site

Table 14. List of activities and data sources

Activity Category	Data Sources
Raw material extraction and transport	• Raw material quantities provided by Lafarge • Transport distances calculated using Google Maps • Transport emission factors from GHG Protocol • Extraction emission factors primarily from Zhang and Mabee
Fuel extraction and transport	• Fuel use data provided by Lafarge • Upstream coal extraction emission factor based on Zhang and Mabee, 2016 • Diesel and gasoline extraction emission factors from Natural Resources Canada's GHGenius • Natural gas extraction emission factor from Pembina analysis of Canada National Inventory Report 2018 • Transport emission factors based on GHG Protocol and Transcanada Pipeline data
Alternative fuel processing	• Emission factors and methodology from Zhang and Mabee
Plant operation – fuel combustion	• Kiln and non-kiln fuel consumption provided by Lafarge • Kiln and non-kiln fuel emissions provided by Lafarge • Alternative fuel heating values and combustion emission factors provided by Lafarge
Plant operation – kiln process emissions	• As calculated with the World Business Council on Sustainable Development spreadsheet emission factors, provided by Lafarge
Landfill emissions	• Landfill emission factors from Zhang and Mabee